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13. ABSTRACT *(Maximum 200 words)*

The program involved a series of individual projects coordinated to develop controls for a flexible light weight robot arm. A hydraulically actuated 3-link robot arm was installed on a PRAB hydraulic base, and was designed of tubular steel. A PERT program chart was prepared (appendix B) on which various inter-related project milestones were projected.

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RESEARCH IN LIGHTWEIGHT ELASTIC ROBOTIC ARMS

FINAL REPORT

JUNE 30, 1993

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FINAL REPORT

ARO ROBOTICS PROGRAM

The ARO Robotics Program at the Howard R. Hughes College of Engineering of the University of Nevada, Las Vegas, has been housed in the Department of Civil and Mechanical Engineering, and more recently in the Department of Civil and Environmental Engineering with cooperation from the Department of Electrical Engineering.

Problem Studied:

The program involved a series of individual projects coordinated to develop controls for a flexible light weight robot arm. A hydraulically actuated 3-link robot arm was installed on a PRAB hydraulic base, and was designed of tubular steel. A PERT program chart was prepared (appendix B) on which various inter-related project milestones were projected. These were accomplished by individual researchers with the assistance of graduate and undergraduate students over the last six years. Each researcher has prepared a summary of his results, which follow this introduction.

A total of twelve Masters Theses were produced, eighteen papers were presented at technical meetings, thirteen papers were published in peer reviewed journals, seventeen conference reports were completed, as well as a number of senior design reports of undergraduates. These are summarized in Appendix A.

During the course of research from June 1987 through June 1993, eight faculty researchers took part in the program, fourteen graduate students, and a number of undergraduate students. In June 1993 two graduate students were using the Robotics equipment for research: Bassel Abdelnour and Shashidhar Channarayapatna.

We believe the Robotics Program has been a great success to the College and to the University. This Program initiated professional research to the new College of Engineering, allowing early growth of the Master's Degree Program. It provided financial support for two new faculty (Yim and Trabia), graduate students, undergraduate students, and summer support for regular faculty.

Summary of Results of Research Completed on the ARO Robotics Project:

Dr. William Culbreth
Dr. Samaan Ladkany
Dr. Sahjendra Singh
Dr. Mohamed Trabia
Dr. Woosoon Yim

Summary of Results of Research Completed on the ARO Robotics Project

Dr. William Culbreth, Associate Professor of Civil Engineering:

1. Simulation of an Elastic Robotic Arm

Computer simulations were developed of the elastic robotic arm to demonstrate the static deflections expected under load and to predict the motion of the arm under acceleration. Simulation software was prepared for two computer platforms as the project progressed.

Early in the project, a robot test system was designed by combining a commercial robot hydraulic base, elastic arms manufactured on-site, hydraulic actuators, and sensors. In the first phase of computer simulation of the robot, a computer program, ROBOT8, was written for the IBM-PC to assist researchers in the selection of components for this test system. The computer program was written in QuickBASIC and determined the robot workspace, the required static loads in the actuators, and the forces experienced at each joint. This code predicted the static position of each joint and the end effector and provided a visual verification of the stops on each joint. This code was used in the selection of hydraulic actuators, encoders, and in the design of the length of each elastic member. The use of this code and sample results are provided in Reference 1.

In phase two of the robot simulation work, a robust computer graphics platform was purchased to simulate elastic effects in the robot. The workstation, a Silicon Graphics 3130 IRIS unit, came with a high-resolution color monitor, a dial-and-button box, and a mouse. The computer utilized the UNIX operating system and was ordered with a Fortran 77 compiler. A simulation code was written with the following objectives in mind:

1. Model three degrees-of-freedom utilizing a revolute geometry robot with hydraulic actuators.
2. Compute and display the static deflection of each segment.
3. Based on input containing velocity and acceleration data, compute and display the resulting robot motion.
4. Based on varying force in each hydraulic actuator, predict the resulting motion of the elastic robot including joint position, velocity, and acceleration.
5. Accommodate various segment lengths, actuator locations, and stop positions easily.
6. Display all motions in 3-D with the ability to change the world view.

Allison Kreuger, an Engineering graduate student, completed this extensive simulation code of the elastic robot as part of her Master's Program. (see reference 2) The simulation required an indepth knowledge of the kinematic equations that governed the elastic robot motion. Her code was written in Fortran 77 with extensive use of the hardware graphics capabilities of the IRIS workstation. This code met all of the requirements set down in the objectives and, due to the high speed of the graphics hardware in the workstation, provided some interesting dynamic simulations. During one particular simulation, the elastic arm was allowed to drop from a horizontal position and allowed to fall against the stops. The simulated robot obediently struck the stops and elastically rebounded with a resulting complex motion of the two elastic segments.

2. Hydraulic Pressure Measurements on the Test Base

To facilitate research on elastic robots, a test base was constructed early in the project. This test base consisted of a Prab unimate 1005 hydraulic base with a vertical rotating shaft, a hydraulic controller, two elastic segments, encoders and two additional hydraulic actuators. Numerous sensors were attached to the base and to each joint to determine position, acceleration, deflection, and strain. A set of IBM-PC/AT-compatible computers with 80386 microprocessors and data acquisition cards were used to control the robot and acquire sensor outputs. The robot was controlled by sending a signal to the servoamplifiers that controlled each hydraulic actuator.

To control the robot, data was needed on the actual dynamic forces exerted by each hydraulic actuator. To obtain this information and to make it available to the controller algorithm, pressure transducers were attached to each part of the hydraulic actuators. This first phase of work involving pressure measurements from the hydraulic actuators was accomplished in the following steps:

1. Diaphragm pressure transducers with a range of 0 to 2000 psig were purchased.
2. Instrumentation amplifier boards were designed and constructed for each transducer.
3. Due to signal noise, lowpass filters were designed and constructed.
4. The transducers were connected through the signal conditioning modules to the 12-bit analog-to-digital converter on the 80386 computer. Routines were written to acquire the data in C.
5. The transducers were calibrated with a deadweight tester.

This work was conducted by Andreas Ranz and is documented in reference 3.

Phase 2 of this work involved the servoamplifiers that power each hydraulic actuator. The control algorithms required a transfer function that defined the force expected in each hydraulic actuator as a function of the voltage fed into its corresponding servoamplifier. Determination of the transfer function required that two "constants" be determined: a pressure coefficient and a flow coefficient. To measure these values, the robot had to be moved throughout its workspace under both constant velocity and constant pressure conditions. A PID controller was written to meet these conditions and the computer monitored pressure transducer output as a function of voltage input to the servoamplifiers. The voltage output was produced by a 12-bit digital-to-analog converter in the computer. A map of the flow and pressure constants was measured as functions of robot geometry, velocity, and acceleration.

Dr. Samaan G. Ladkany, P.E., Professor of Civil Engineering:

I. Introduction

A decision was made by the ARO Project researchers at the start of the project to design a one-third scale three meter long hydraulically actuated robot having a natural frequency that varies between 0.5 Hz to 6 Hz depending on load carried and position of the links.

II. Robot Design

The robot was designed of tubular steel and was installed on a PRAB hydraulic base.

The structural and dynamics aspects of the robot design were the subject of Tarek M. Bannoura's thesis entitled "Structural Analysis and Design of a Flexible Three-Link Hydraulically Actuated Robotic Arm".

The design was the subject of a presentation at the SME World Conference on Robotic Research in Gaithersburg, Maryland. A paper authored by S.G. Ladkany and T.M. Bannoura, entitled "Structural Design of a Flexible Three-Link Hydraulically Activated Robotic Arm", Paper #MS89-25, 1989, appeared in the conference proceedings and printed in the <u>Journal of the Society of Manufacturing Engineering</u> as a journal publication.

III. Dynamic Response of the Robot

Studying the complex dynamic response of the three-link flexible robot was the subject of Robert F. Marceau's thesis entitled "Dynamic Response of a Flexible Three-Link Robot Using Strain Gauges Lagrange Polynomials, Fourier Series and the Finite Element Analysis".

Strain readings are obtained from a set of 24 strain gauges and four rosettes. The deformed shapes of the links are predicted from strain gauge readings and the exact position of the end effector is accurately predicted.

This research was the subject of a presentation at the Fourth World Conference on Robotics Research, Pittsburgh, Pennsylvania, October 1991, the written version appeared in the conference proceedings. The full paper was published in the <u>Journal of the Society of Manufacturing Engineering</u> and was authored by S.G. Ladkany and R.F. Marceau, 1991.

IV. Laboratory Investigations

The robot was built of tubular steel and was tested under static and dynamic loading conditions.

The robot was outfitted with twelve sets of strain gauges and two sets of rectangular strain gauge rosettes. The sensors were tested separately and then linked to a Keatly Dynamic Acquisition System and two 80-486 AT's computers, one used for controlling the movements of the robot and the other used for data acquisition from the Keatly equipment and for feed-back in order that active damping and control may be achieved.

The experimental work was started by R.F. Marceau with the help of P. Rejeski under the direction of Dr. Ladkany and is currently the subject of the Masters Thesis of Bassel Abdelnour. This research is under the joint supervision of Drs. Ladkany and Trabia.

Dr. Sahjendra N. Singh, Professor of Electrical Engineering:

Research has been done to control multi-link robotic systems. Controllers and stabilizer design consider structural flexibility, and payload uncertainty. Nonlinearity in the system has been retained for obtaining a more realistic representation. The following seven control systems have been designed.

1. Variable structure control of rigid arm
2. Inverse control and stabilization of Elastic Arm
3. Adaptive control and stabilization of Elastic Arm
4. Sliding mode control of elastic arm
5. Ultimate boundedness control of elastic arm
6. Inverse end point trajectory control of elastic arm
7. Sliding mode end point trajectory control

Below we discuss each of these control systems.

1. Variable Structure Control of a Robotic Arm (without structural flexibility)

Based on the theory of variable structure systems (VSS), control system design for the trajectory control of robotic systems is presented. It is assumed that the parameters of the system are uncertain and unknown frictional torques are acting at the various joints of the arm. For simplicity, the control of a three-link PUMA arm is considered. For trajectory following, two control laws, C_H and C_e based on the choice of coordinates of the end effector or joint angles as the controlled outputs, respectively, are derived. It is seen that whereas control C_e has no singularity, certain singular surfaces arise where feedback elements of C_h become infinity. These singular surfaces describe the boundary of the reachable region (workspace). Digital simulation results are obtained to show that accurate trajectory following can be accomplished using the control C_H or C_e for large maneuvers of the arm in spite of the uncertainty in the system.

2. Inverse Control and Stabilization of Elastic Arm

We consider control of an elastic robotic arm of two links based on non-linear inversion and pole assignment for stabilization. The design is performed in two steps. First, based on non-linear inversion, a non-linear controller is designed for the trajectory control of the joint angles using joint torquers. The inverse controller accomplishes trajectory control of the joint angles. This excites the elastic modes of the arm. In order to damp the elastic oscillations, a stabilizer is designed for a linearized system about the terminal state using the pole assignment technique. In the closed-loop system, first the inverse controller acts when a command is given, then the stabilizer automatically switches when the joint angle trajectory enters a specified neighborhood of the final commanded position. Simulation results show that in the closed-loop system accurate joint angle trajectory tracking and elastic mode stabilization can be accomplished in spite of payload uncertainty in the system.

3. Ultimate Boundedness Control of Flexible Arm

We treat the question of control of an elastic robotic arm of two links. Of course this approach can be extended to other elastic arms. A nonlinear ultimate boundedness controller (UBC) is synthesized such that in the closed-loop system, the joint angle tracking error is uniformly bounded, and tends to a certain small neighborhood of the origin. The controller includes a reference joint angle trajectory generator and integral error feedback. Although, the joint angles are controlled using the UBC, elastic modes are excited. A feedback stabilizer is designed for the linearized model including the UBC about the terminal state which is switched only in the vicinity of the equilibrium state for stabilization. Simulation results are obtained to show that in the closed-loop system including the UBC and the stabilizer, accurate joint angle trajectory following and elastic mode stabilization are accomplished in the presence of uncertainty.

4. Inverse End Point Trajectory Control of Elastic Arm

The question of control of the effector trajectory and stabilization of two-link flexible robotic arm is considered. A control law based on the inversion of an input-output map is obtained. The outputs are chosen as the sum of the joint angle and tip elastic deformation times a constant factor for each link. The stable maneuver of the arm critically depends on the stability of the zero dynamics of the system. Stability of the zero dynamics is shown to be sensitive to the choice of the constant multiplying factor, which explains the difficulty in controlling the tip position. Although the inverse controller accomplishes output control, this excites the rigid and elastic modes. Simulation results are obtained to show that in the closed-loop system, large maneuvers can be performed in the presence of payload uncertainty.

5. Sliding Mode End Point Trajectory Control of Flexible Arm

The question of control and vibration suppression of the end effector for a two link manipulator based on variable structure system theory is considered. Since the zero dynamics corresponding to the tip position control is unstable, sliding mode controller for the a control a point closed to the tip of links is considered. Stabilizer is designed for vibration suppression. Digital simulation results show that larger payload uncertainty can be tolerated compared to the inverse controller and precise end point trajectory can be accurately tracked in the closed-loop system.

Conclusions:

For high performance manipulators it is essential to design sophisticated control systems which can accomplish large, nonlinear, fast maneuvers. However, fast maneuver leads to significant nonlinearity in the system. Furthermore, in order to obtain efficient operation it is essential to have light manipulator links. The nonlinearity and elasticity pose significant difficulty in control system design.

Several control laws based on nonlinear inversion, variable structure control theory, adaptive control theory and Lyapunov derivations nonlinearity of the arm has been retained. Extensive numerical simulations have been performed to evaluate each of the control schemes. Simulated responses show that in the closed-loop system large. fast maneuvers and elastic modes stabilization can be accomplished in spite of payload variations.

Dr. Mohamed B. Trabia, Assistant Professor of Mech. Engineering:

Mechanical Design of the UNLV/ARO Flexible Robot

The design process started by synthesizing the robot dimensions in order to maximize the robot workspace volume. All the aspects of the robot mechanical design are finished. These aspects included design and machining of the robot segments, selection of the actuators for joints 3 and 4, selection of the servoamplifiers for the same joints, and machining of the robot platform. The pneumatic robot gripper is installed. Plots of the robot workspace boundaries are included.

Robot Platform Experiment Preparations

The experimental work is aimed at the control of the 3-segment elastic robot arm. The first step was to install the joints servoamplifiers. Joint angle data is provided by the joint encoders. Manual control of the robot is completed. The robot is currently controlled through 386 AT compatible computer. The A/D and the D/A units for all the robot joints encoders and servovalves have been installed and tested (B. Abdelnour).

C subroutines have been written that interface to the controls program under development by M. Trabia. Control program for moving the hydraulic robot through the workspace is finished. The robot software necessary for driving the joints servoamplifiers using the encoders inputs is done. The program is able to move the robot between any points within the robot workspace at varying speed. Home position is also defined. The program measures the joints angular speed and pressure at the hydraulic cylinders through the motion.

Robot Modeling and Control

Deriving the elastic robot dynamic equations of motion for the following cases has been completed,

1. Three links, the two outermost ones are elastic, in-plane deformation, no hydraulic actuators
2. Three links, the two outermost ones are elastic, in-plane and out-of-plane deformations, no hydraulic actuators
3. Three links, the two outermost ones are elastic, in-plane and out-of-plane deformations, hydraulic actuators and the effect of their elasticity

The derivation is done using MACSYMA (E. Lam's Thesis). These equations are incorporated into a Fortran Program for robot dynamic simulation. IMSL package is used to solve these equations. This program may be used as a basis for robot control analysis and for studying ways to reduce the robot vibrations. This work resulted in a general algorithm for deriving the equations of motion of flexible robots and controlling the size of equations in the meantime.

The direct dynamic problem of the flexible robot is studied (Satish Jupudi's Thesis). Effects of eliminating nonlinear terms from the model of the flexible robot model are considered. A program for controlling the vibrations of three links, the two outermost ones are elastic, in-plane and out-of-plane deformations, no hydraulic actuators robot using feedback controller is almost finished (in cooperation with Dr. S. Singh).

Dr. Woosoon Yim, Assistant Professor of Mechanical Engineering:

1. Controller Design and Implementation for Two-Axis Flexible Robot Arm

This research focuses on the implementation of a flexible robot controller for the maneuver of a two-axes flexible robotic arm. The joint angle trajectory tracking is accomplished by a proportional and derivative (PD) and a feedforward controller. Based on the pole placement technique, linear stabilizers are designed for each axis for elastic mode stabilization in the plane perpendicular to each joint axis. The stabilizers are switched on when the trajectory reaches the vicinity of the terminal state. The effect of switching time of the stabilizer and varying payload on arm vibration are investigated.

Configuration

Two servo motors (Inertial Motors Co., Model D30-E and D30-S) with speed reducers (Harmonic Drive, Model PCR1M and PCR3C) are used for the first and second joint actuator respectively. The axes of two motors are perpendicular to each other. The first motor is mounted on a frame which is rigidly fixed to the ground and the second motor is mounted on a bracket which is fixed on the shaft of the first motor. The flexible arm, which is a steel rod, is attached on the shaft of the second motor. If the elastic modes of the rod are excited by a combined motion of these two motors, the vibration of the tip of the rod will have two components. One is along the latitude of the work space sphere which we call the out-of-plane vibration, the other is along the longitude of the sphere which we call in-planer vibration. A lateral effect photodiode (UDT LSC30) with a diode laser generator (780nm) is used as a link tip deflection sensor as shown in Fig. 2. The photodiode provides a position information (x,y) of a laser spot in a two-dimensional sensor surface with its origin at the center of the sensor. A bandpass filter is used on the front of photodiode to filter out the ambient light.

Controller

In the proposed controller, the trajectory evolves in two phases. In the first phase of maneuver, the joint angles are controlled and in the second phase, in-plane and out-plane vibration suppression are accomplished. For a joint angle trajectory control, a PD controller is synthesized for each joint axis based on an experimentally identified servo motor models. An input shaping filter is designed in the feed-forward loop so that a ramp command trajectory can be tracked. Using the joint angle controller, the arm can be maneuvered to follow a given joint angle trajectory command. However, this excites the elastic modes, and it becomes necessary to damp the elastic motion.

The advantage of using the joint angle controller is that when the joint angle reaches the vicinity of the terminal state, the only significant motion remaining in the system is due to elastic vibration. Thus in the terminal phase, the system is well represented by a linear model since in the robot arm model only significant nonlinearity is due to the rigid mode.

Based on an asymptotically linearized model, a stabilizer is designed using the pole placement technique. For the synthesis of the controller, only measured variables are used. The elastic mode is obtained by an optical deflection sensor consisting of a diode laser and a two-dimensional position photodiode. The derivative of the elastic mode feedback is obtained by digitally differentiating the measured deflection signal of link tip position. The complete closed-loop system is synthesized in laboratory and experiments are performed to verify joint angle tracking and vibration stabilization capability to follow various command trajectories. Sensitivity of the controller to payload variations and the effect of smooth command trajectories on elastic deflection are also examined. Although the stabilizer has been designed for the terminal phase, experimental results indicate that the control system is quite robust and one can leave the stabilizer loop closed throughout and still stable response are obtained.

2. Optimum Joint Angle Trajectory Planning

Based on the dynamic model of a flexible robotic arm, optimum joint angle trajectories are determined for the minimum link deformation. The cycloidal motion profile is used as a base function and a switching point between joint acceleration and deceleration becomes the design variable. Computer simulation of one and two elastic links cases was done. This open-loop control scheme was implemented to a experimental DC motor driven robotic arm to improve the performance of the vibration stabilizer at the final target position of arm.

3. Design of an Optical Link Deflection/Slope Transducer

For a direct measurement of link tip deflection and slope, an optical technique was chosen. This transducer consists of a diode laser generator and two-dimensional lateral effect photodiodes. Accuracy of the transducer is approx. 0.1 mm, and the maximum measurable deflection is approx. 25 mm. This transducer was used for an elastic mode feedback of the vibration stabilizer along with the joint encoder and tachometer feedback. In the experiment, it was shown that this deflection sensor can be used effectively for on-line estimation of the static deflection of the link at the target position for an unknown payload.

Participating Scientific Personnel:

Dr. William A. Culbreth, Professor of Civil Engineering
Dr. Samaan Ladkany, Professor of Civil Engineering
Dr. George Mauer, Assoc. Professor of Mech. Engineering (1986-88)
Dr. Douglas Reynolds, Professor of Mech. Engineering (1986-88)
Dr. Sahjendra Singh, Professor of Electrical Engineering
Dr. Mohamed Trabia, Asst. Professor of Mech. Engineering
Dr. Richard Wyman, Professor of Civil Engineering
Dr. Woosoon Yim, Asst. Professor of Mech. Engineering

Listing of Advanced Degrees Earned While Participating in the Project:
Master's Degrees Granted to Researchers:

Edward Lam	MS	1990
Satish Jupudi	MS	1992
Bassel Abdelnour	MS	1992
A. Das	MS	1989
P.J. Nathan	MS	1989
S.K. Madhavan	MS	1991
A. Kreuger	MS	1989
A. Ranz	MS	1991
Yung Ming Hu	MS	1990
Jichun Zuang	MS	1991
R.F. Marceau	MS	1990
Tarek Bannoura	MS	1989

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2. T. M. Bannoura, "Structural Design of a Flexible Three-Link Hydraulically Activated Robotic Arm", 1989.

3. A. Das, "Decoupling Adaptive Control and Stabilization of Two Link Elastic Robotic Arm," 1989.

4. Y.M. Hu, "Optimum Joint Angle Trajectory Planning for a Robot With Elastic Links", Department of Mechanical Engineering.

5. S. Jupudi, "Mathematical Modeling, Trajectory and Vibrations Control of a Three-Link Flexible Robot", February, 1992.

6. A.J. Kreuger, "Three Dimensional Computerized Model For Elastic Robotic Arm", 1989.

7. E. Lam, "Modeling of Hydraulically Activated Robot With Flexible Links", April, 1990.

8. S.K. Madhavan, "Inverse and Variable Structure Trajectory Control of a Flexible Robotic Manipulator," 1991.

9. R.F. Marceau, "Dynamic Response of a Flexible Three-Link Robot Using Strain Gauges, LaGrange Polynomials, Fourier Series, and Finite Element Analysis", 1991.

10. P.J. Nathan, "Variable Structure and Ultimate Boundedness Control and Stabilization of Flexible Robotic Arm," 1989.

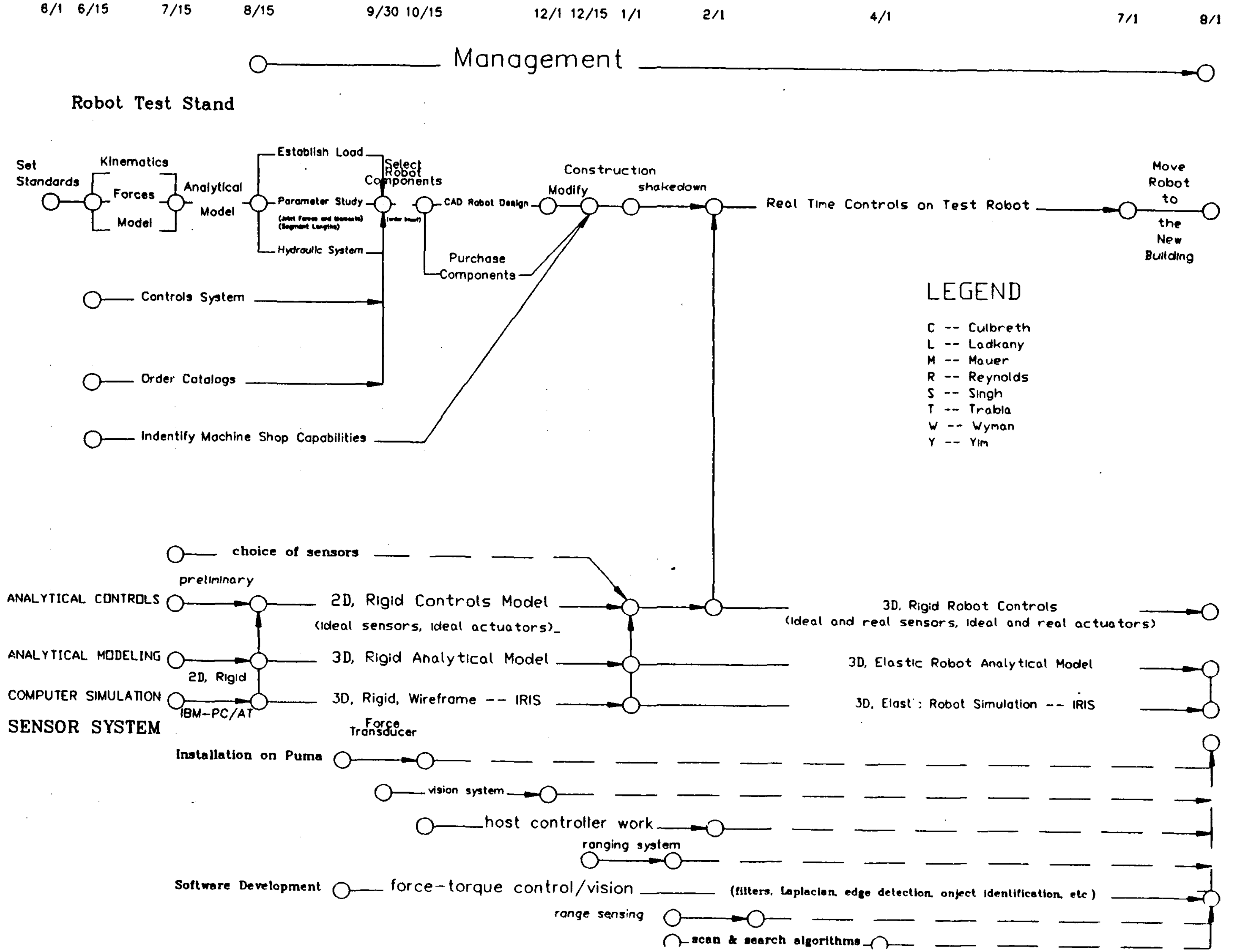
11. A.V. Ranz, "System Identification of a Hydraulically-Actuated Robot", 1991.

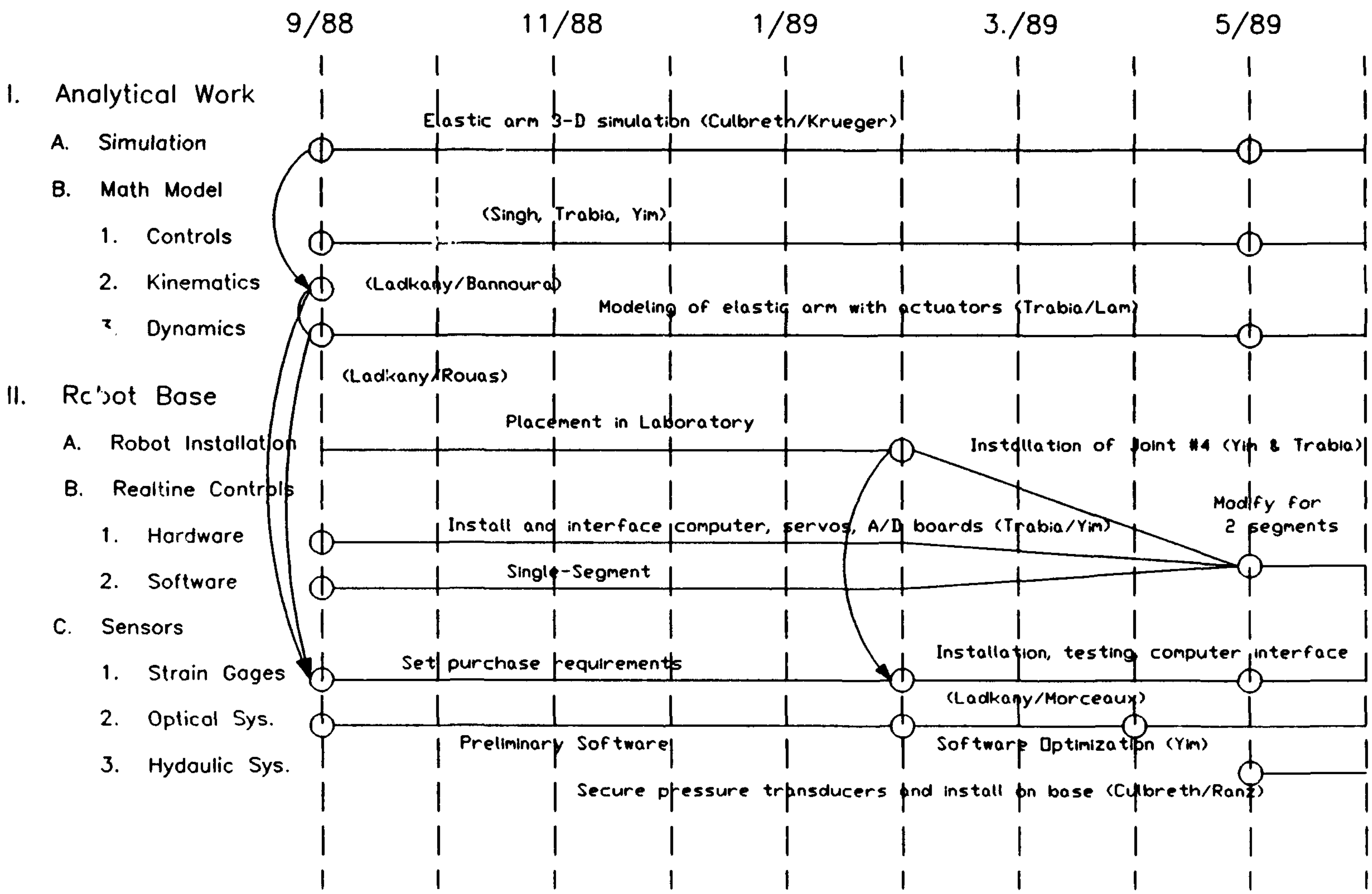
12. J. Zuang, "Experimental Two-Axis Vibration Suspension Control of a Flexible Robot Arm", 1991.

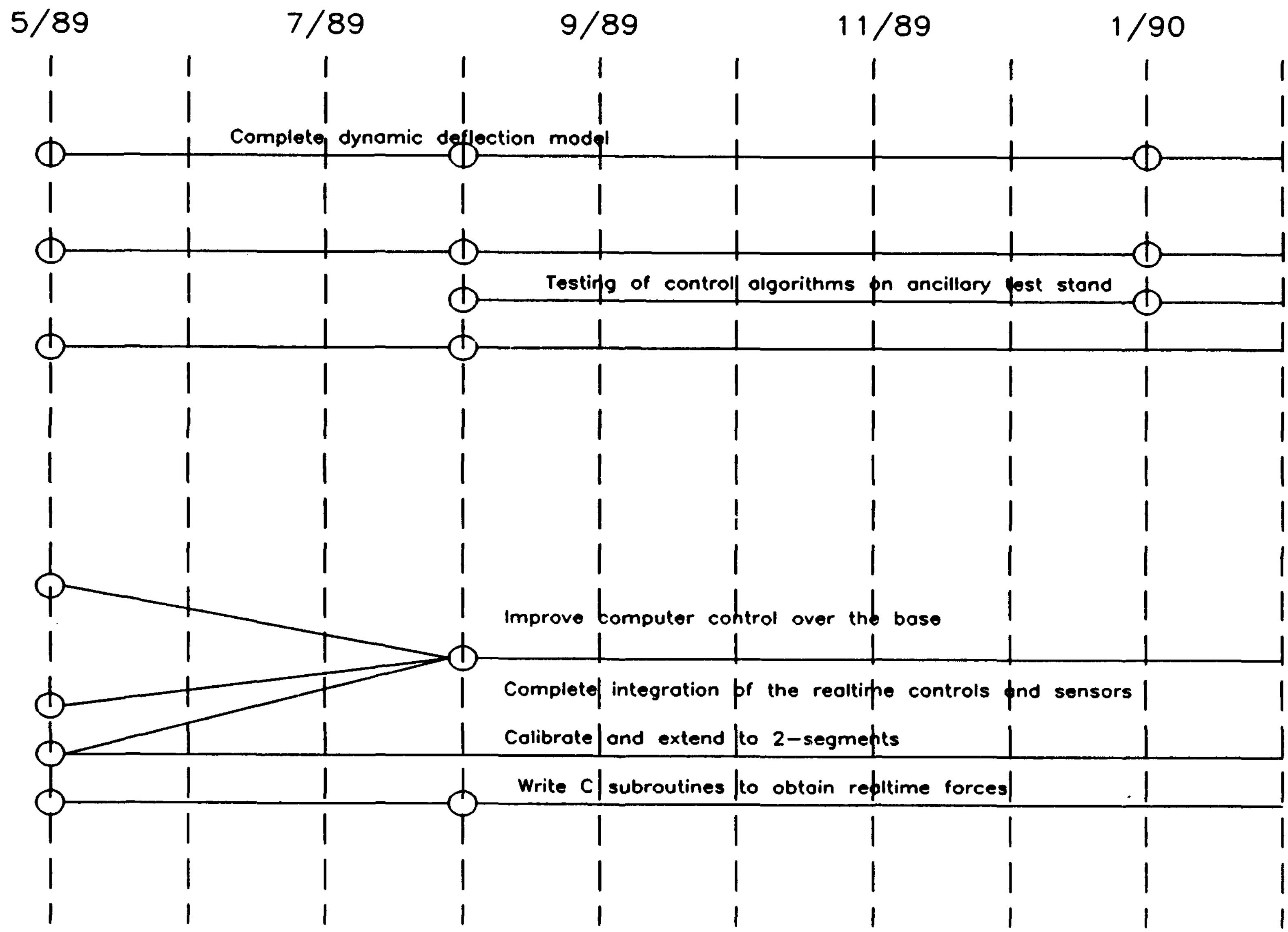
UNLV/ARO ROBOTICS RESEARCH PROJECT

Robot Test Stand Schedule, 6/17/87 · Controls and Modeling Schedule, 7/15/87 WGC, 9/22/87

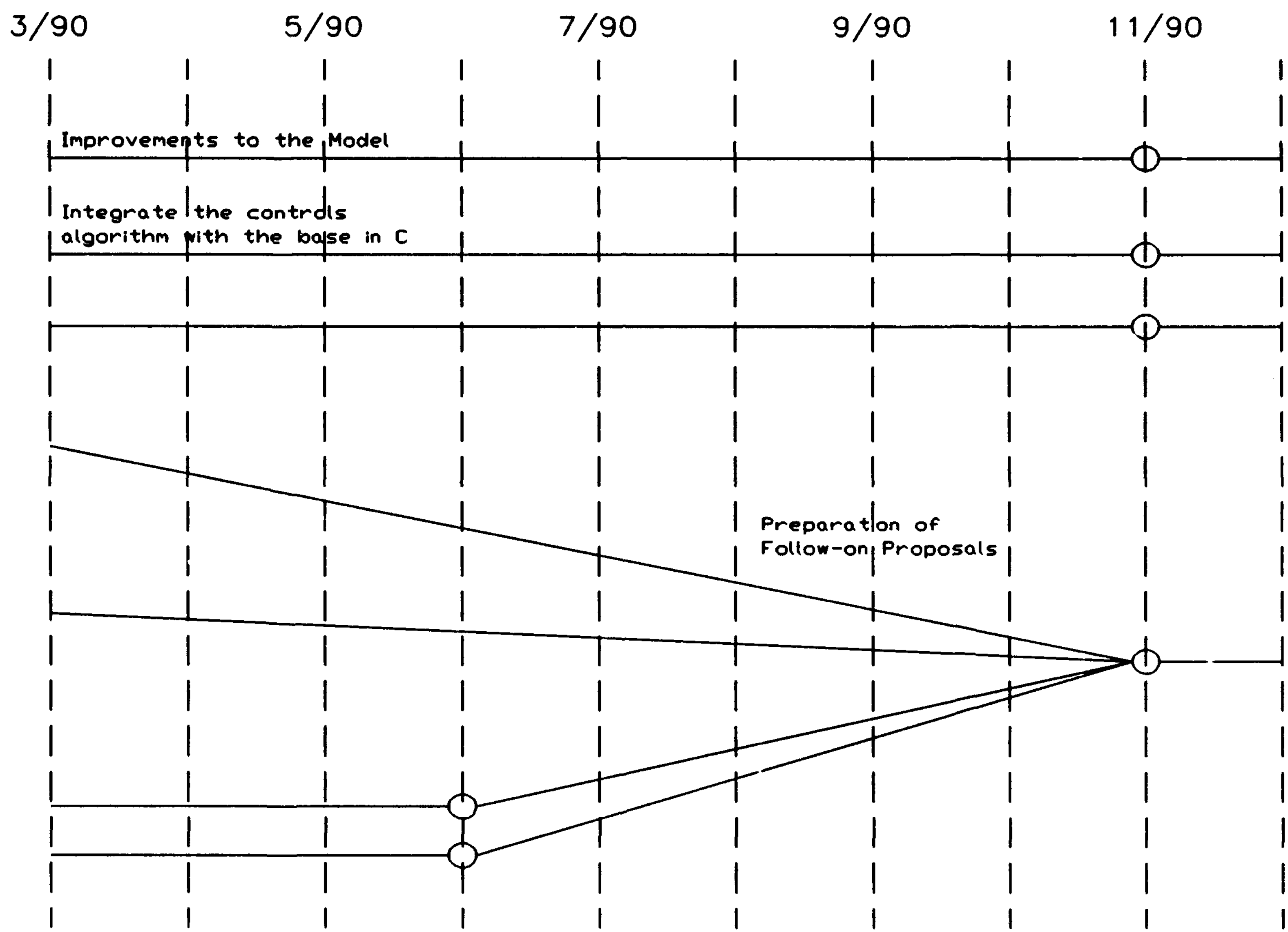
Vision/Sensor System, 9/10/87

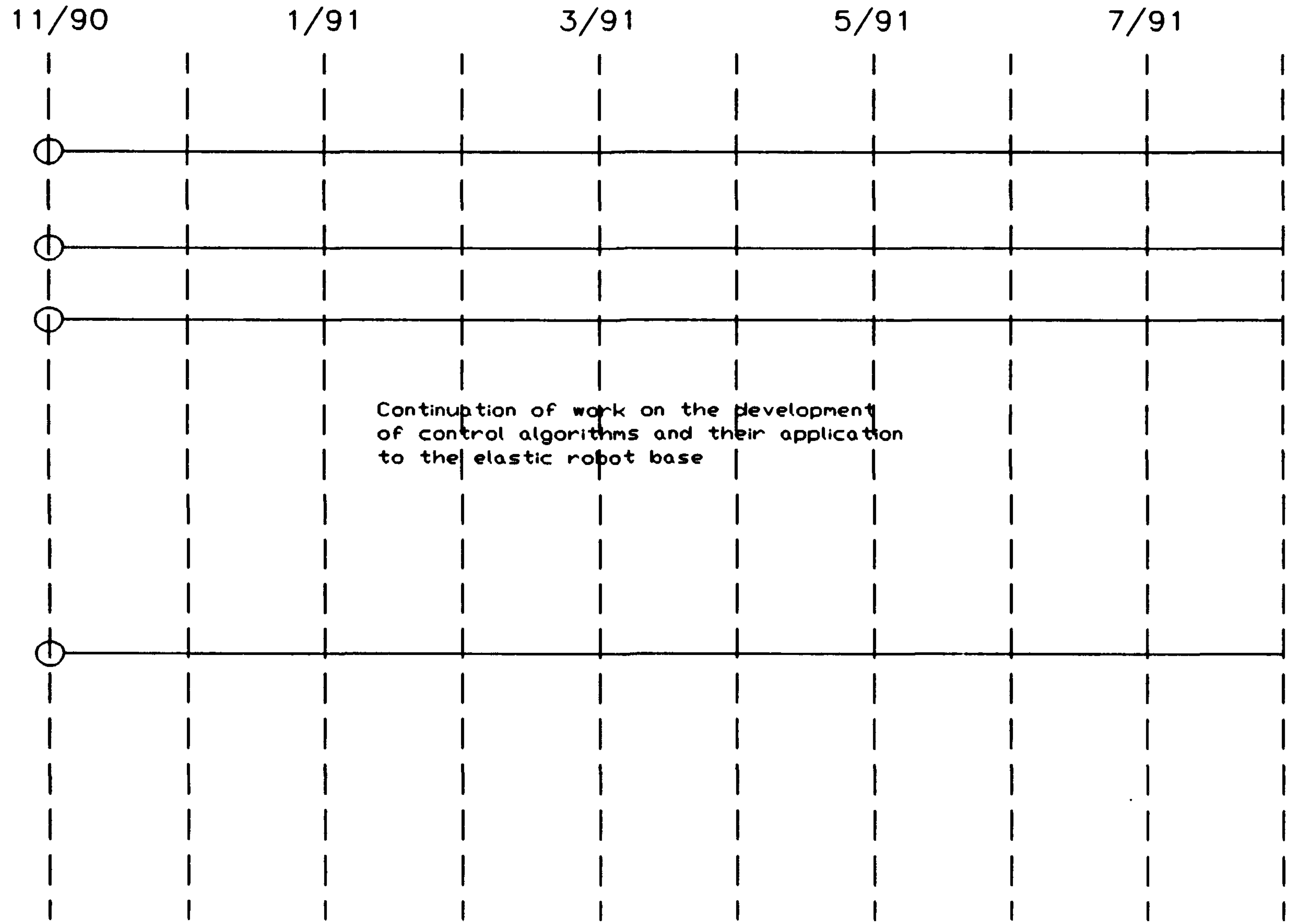


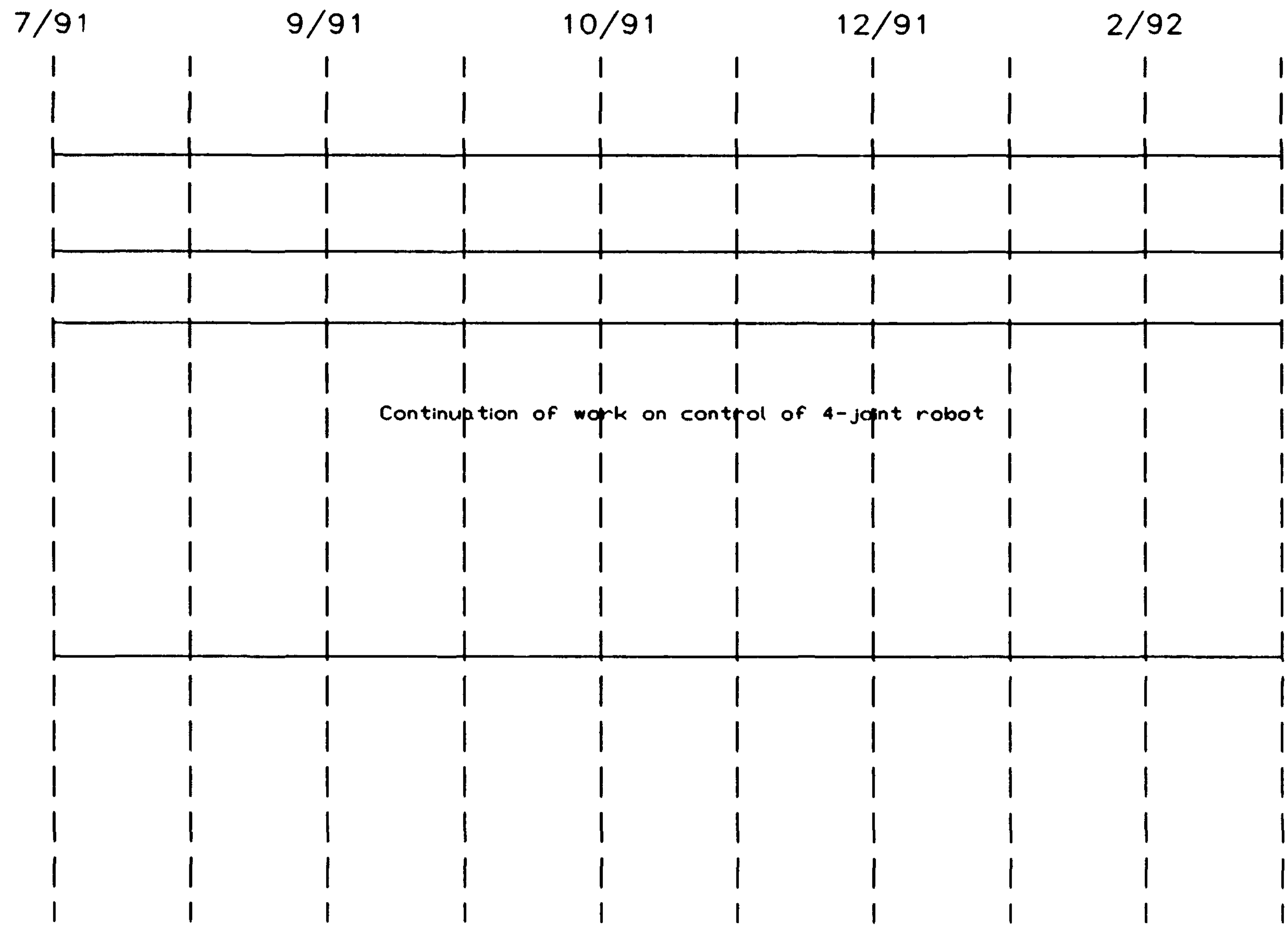

9/88
11/88
1/89
3./89
5/89
I. Analytical Work
A. Simulation
B. Math Model
1. Controls
2. Kinematics
3. Dynamics
II. Robot Base
A. Robot Installation
B. Realtine Controls
1. Hardware
2. Software
C. Sensors
1. Strain Gages
2. Optical Sys.
3. Hydaulic Sys.
Elastic arm 3-D simulation (Culbreth/Krueger)
(Singh, Trabia, Yim)
(Ladkany/Bannoura)
Modeling of elastic arm with actuators (Trabia/Lam)
(Ladkany/Rouas)
Placement in Laboratory
Installation of Joint #4 (Yim & Trabia)
Modify for
2 segments
Install and interface computer, servos, A/D boards (Trabia/Yim)
Single-Segment
Installation, testing computer interface
Set purchase requirements
(Ladkany/Morceaux)
Preliminary Software
Software Optimization (Yim)
Secure pressure transducers and install on base (Culbreth/Ranz)

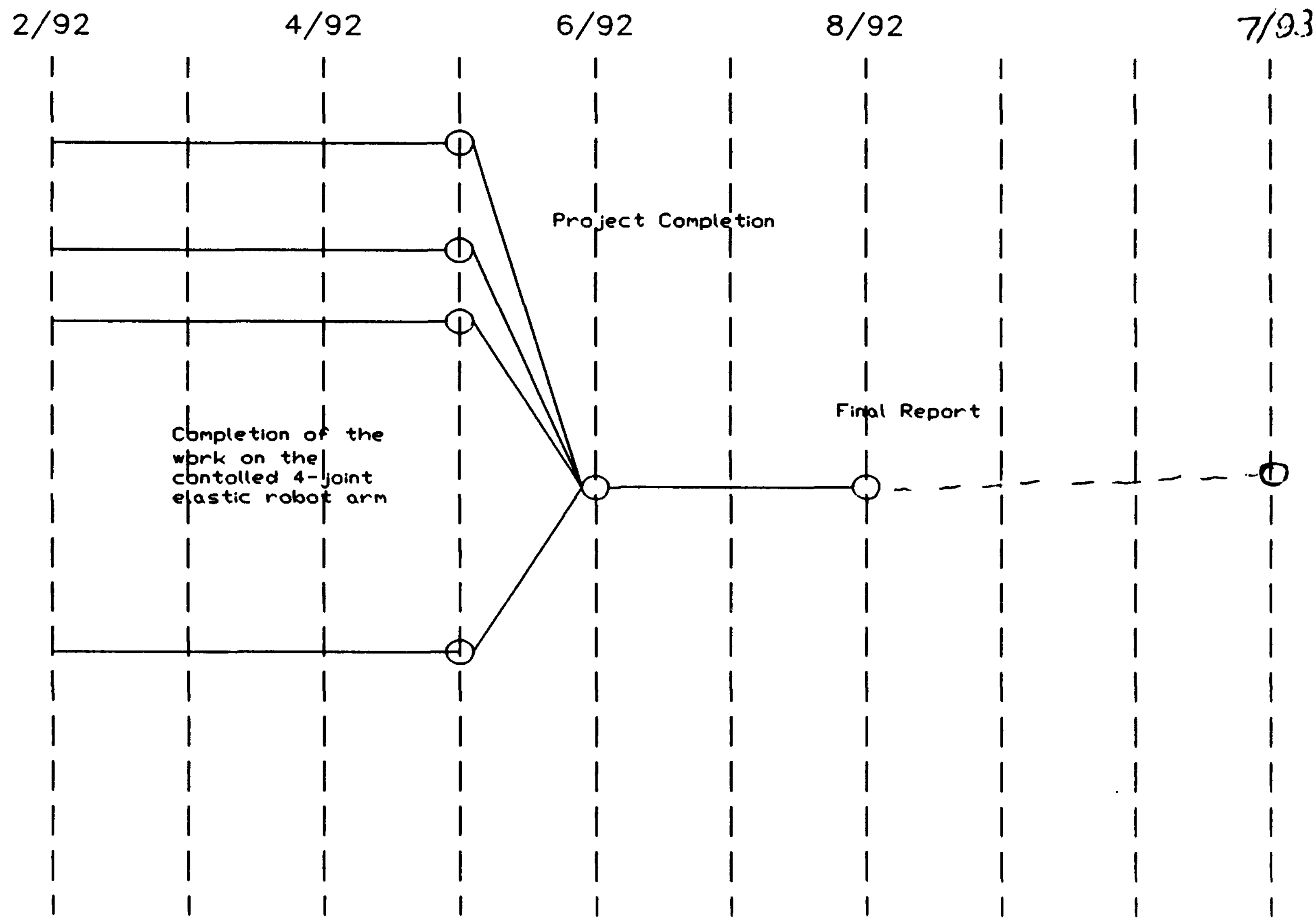


5/89
7/89
9/89
11/89
1/90
Complete dynamic deflection model
Testing of control algorithms on ancillary test stand
Improve computer control over the base
Complete integration of the realtime controls and sensors
Calibrate and extend to 2-segments
Write C subroutines to obtain realtime forces


3/90
5/90
7/90
9/90
11/90
Improvements to the Model
Integrate the controls
algorithm with the base in C
Preparation of
Follow-on Proposals


11/90
1/91
3/91
5/91
7/91
Continuation of work on the development
of control algorithms and their application
to the elastic robot base


7/91
9/91
10/91
12/91
2/92
Continuation of work on control of 4-joint robot


2/92
4/92
6/92
8/92
7/93
Completion of the work on the contolled 4-joint elastic robot arm
Project Completion
Final Report